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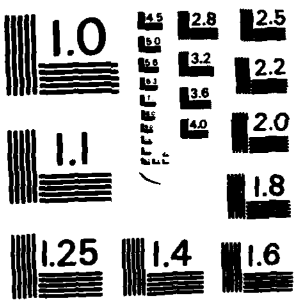
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AN ESTIMATION METHOD OF VERTICAL DIFFUSION PARAMETERS IN THE MESOSCALE RANGE

by

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AN ESTIMATION METHOD OF VERTICAL DIFFUSION PARAMETERS IN THE MESOSCALE RANGE

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Based on the hypothesis of similarity for local turbulent characteristics in planetary boundarg layers and the principle of dimensional analysis, and using statistical form of the vertical vortex diffusion coefficient K as well as Ekman spiral wind profile, at vertical dispersion pattern in the 100 km range is derived by numerical analysis method. It is applicable to both flat uniform land and complex terrain. The results so far obtained agree fairly with experimental data.

I. INTRODUCTION

During the past decade, the long range pollution arising from cities and super-high chimneys has become worse and worse. This has forced air pollution meteorologists to take an interest in the study of laws governing transport-diffusion in the mesoscale range (10-100 km). However, owing to limitations on methods of observation and on the understanding of mesoscale processes, both the diffusion theories and field observations and tests are still in an embryo stage, and are far from being able to meet the demands of the various environmental problems.

In this paper, we attempt to use the hypothesis of similarity for local turbulent characteristics in planetary boundary layers and the principle of dimensional analysis to perform a numerical analysis, and present an estimation method for obtaining a vertical diffusion parameter σ_z that is applicable in the 100 km range.

*Comrade Yen Pang-liang has participated in part of the computational work.

II. DERIVATION OF FORMULAS

According to the hypothesis proposed by Pasquill [1] that the local turbulent flow characteristics are similar in planetary boundary layers, the average rate of increase of $\bar{z}$ (the mean vertical displacement of the diffusing particle) is determined by two local parameters only, viz. σ_w (standard deviation of vertical pulsating velocity and λ_m (turbulent flow dimension in the vertical direction). These two quantities are functions of height and are, therefore, also related to the thermodynamic layer. One can obtain from dimensional analysis

$$\frac{d}{dt}\bar{z}=\sigma_w(\bar{z})f\left[\frac{\lambda_m(\bar{z})}{z}\right] \tag{1}$$

where f is a function to be determined. The rate of variation of the average horizontal displacement $\bar{x}$ of the corresponding mass point moving in the same direction as the wind is given by

$$\frac{d}{dt}\bar{x}=u(\bar{z}) \tag{2}$$

Eliminating dt from equations (1) and (2), one obtains

$$\frac{d\bar{z}}{d\bar{x}}=\frac{\sigma_w}{u}f\left(\frac{\lambda_m}{z}\right) \tag{3}$$ /305

It can be seen from equation (3) that if σ_w, σ_m, the distribution of u (average wind speed) with height and the functional form of f are known, then the relation between $\bar{z}$ and $\bar{x}$ can be derived readily by a numerical integration.

1. Statistical form of the vertical vortex diffusion coefficient K.

Combining Taylor's statistical theory and the solution of Fick's diffusion equation, we know that $K=\sigma_w^2 t_L$. After some simple empirical transformations, we can obtain

$$K=\sigma_w\lambda_m/10 \tag{4}$$

t_L is the Lagrangian time measure. From extensive actual measurements [2] (including various different localities and thermodynamic layers), we have

$$\sigma_w^2 \doteq 0.32^2\lambda_m \tag{5}$$

Inserting equation (5) into equation (4), we obtain

$$K = \lambda_m^{4/3}\varepsilon^{1/3}/16 \tag{6}$$

The above three expressions contain four fundamental quantities: ε (power consumption rate of the turbulent flow), K, σ_w and λ_m. Given two of these quantities, then the other two can be derived. Of these, σ_w, λ_m and ε are easier to measure. Thus, one can express K in terms of actually measurable turbulent flow characteristics, and not have to rely on hypothetical mixed lengths. Moreover, the above expression for K is a better representation of the characteristics of the atmosphere.

2. Determination of the function f.

As σ_z and K are similar [3], it is easy to derive

$$\frac{d\bar{z}}{d\bar{x}} = \frac{K}{u\bar{z}} \tag{7}$$

Substituting equation (4) into equation (7), we obtain

$$\frac{d\bar{z}}{d\bar{x}} = \frac{1}{10}\,\frac{\sigma_w}{u}\cdot\frac{\lambda_m}{\bar{z}} \tag{8}$$

Comparison of equations (8) and (3) shows that

$$f\left(\frac{\lambda_m}{\bar{z}}\right) = \frac{\lambda_m}{\bar{z}}$$

It has been given by Ito (1970) [4] that

$$K \,\text{[illegible]}\, \sigma_w\lambda_m = u\bar{z}\frac{d\bar{z}}{d\bar{x}} \tag{9}$$

Except for the coefficients, equations (9) and (8) are completely the same. Thus, it is appropriate to take f to be $\frac{\lambda_m}{\bar{z}}$. To impart more generality to equation (8), we replace $\frac{1}{10}$ with an undetermined parameter α, and regard α as a function of stability. The final form of equation (8) becomes

$$\frac{d\bar{z}}{d\bar{x}} = \alpha\frac{\sigma_w}{u}\left(\frac{\lambda_m}{\bar{z}}\right) \tag{10}$$

3. Selection of expressions for u, σ_w and λ_m

Since the distribution with height of σ_w and λ_m is different for different stability conditions, the expressions used below will be divided into three groups, corresponding to stable, neutral and unstable conditions.

For neutral conditions, we adopt the relations obtained by Yohoyama [5] in the range of 700-1000 m above ground level:

$$\sigma_w = 1.3u_*\left(1 - \frac{\bar{z}}{h}\right) \tag{11}$$

$$\varepsilon = \frac{u_*^3}{kz}\left(1 - \frac{\bar{z}}{h}\right)^2 \tag{12}$$

In the above relations, k is von Karman's constant, taken to be 0.35 throughout the paper, h is the thickness of the PBL, and u_* is a measure of the velocity in the layer close to the ground level. We can derive from equations (11), (12) and (5) that

$$\lambda_m = 2.4\bar{z} \tag{13}$$

For stable conditions, we choose the expressions obtained by Wamser [2] from data acquired on a 300 m tower:

$$\sigma_w = u_*\left(1 - \frac{\bar{z}}{h}\right)\left(1.36 + 0.08\frac{\bar{z}}{h}\mu\right) \tag{14}$$

$$\lambda_m = \bar{z}/(0.36 + 1.37\mu\bar{z}/h) \tag{15}$$

In equations (14) and (15), $\mu = \frac{h}{L}$ is a stability parameter, and L is a measure of the length in the layer close to the ground level.

For unstable conditions, on the basis of the results obtained in references [1] and [5]-[7], we select the following relations which are applicable in the entire PBL:

$$\sigma_w = 1.9u_*\left(1 - \frac{\bar{z}}{h}\right)\left(-\mu\frac{\bar{z}}{h}\right)^{\frac{1}{3}} \tag{16}$$

$$\lambda_m = 5\bar{z} \tag{17}$$

Owing to limitations on theoretical understanding and available experimental data of the upper half of the PBL, there is as yet not a universally accepted expression for σ_w and λ_m. For instance, Pasquill [1] assigned the number 3.2 to the coefficient in equation (13), and pointed out that it is only applicable in the constantstress layer (usually 100 m thick). Beyond that, it first increases with height then becomes constant. From data obtained on a tower, Wamser [2] maintained that this coefficient is 1.33 at 250 m. The value 2.4 that we have adopted in this paper was derived from data obtained at an even greater height (the height attainable by vertical diffusion--600 m). This value is greater than 1.33 and smaller than 3.2, and is thus representative of an average value for this layer. Although the other relations require further analysis and verification, these were nevertheless established on the basis of definite experimental data and theoretical analyses. Using different expressions for different stability conditions is a fairly good representation of the problem.

A good description of the wind speed in the ground level layer, $u(\bar{z})$, has already been given in a formula [8]. However, there is as yet not a satisfactory distribution form for the wind speed that is applicable both in the ground level layer and in the upper PBL. In recent studies on diffusion in the mesoscale range, some authors [9] have suggested the following form for the wind speed profile:

$$u(\bar{z})=G(1-e^{-l\bar{z}}\cos(l\bar{z})) \tag{18}$$

In this equation, G is the geostrophic wind speed, $l=\sqrt{\frac{P}{2K_0}}$, P is Coriolis parameter, whose value is taken to be $10^{-4}s^{-1}$, and K_o is constant eddy diffusivity. In our recent analysis of the wind speed profile at a 320 m tower [10], we found that in the 320 m range, equation (18) is a better description than the power law expression. In order to discuss the relation between $u(\bar{z})$ and the roughness and stability of the substrate, we adopted the following relation given by Tennekes [11] for associating the inner parameter u_* and the outer parameters G, P and z_0:

$$\ln R_0=Q(\mu)+\ln\frac{G}{u_*}+\left[\frac{k^2G^2}{u_*^2}-A_0^2(\mu)\right]^{1/2} \tag{19}$$ /307

In the above equation, z_0 is the effective roughness length [8], Q is a parameter associated with stability, $R_0=\frac{G}{Pz_0}$ is the Rosby number for the ground, $A_0 = \frac{kG}{u_*}\sin\alpha_o$, and α_o is the angle between the geostrophic wind direction and the direction of the wind in the ground level.

Inserting the expressions for R_0 and A_0 into equation (19), we obtain, after some operations and rearrangement,

$$G=\frac{u_*}{k\cos\alpha_0}\left[\ln\frac{h}{z_0}-Q(\mu)\right] \qquad (20)$$

In the above equation, $h\approx\frac{u_*}{f}$ is the thickness of the boundary layer, the value of α_0 varies between 13 and 35°, and to facilitate computation and at the same time not sacrificing generality, we let $\cos\alpha_0\approx1$. Thus, equation (20) becomes

$$G=\frac{u_*}{k}\left[\ln\frac{h}{z_0}-Q(\mu)\right]. \qquad (21)$$

III. EXPRESSION FOR σ_z FOR FLAT UNIFORM LAND

Flat uniform land refers to the ideal condition where the effective roughness length z_0 = 0.01m. To facilitate comparison between our results and the available standard vertical diffusion types [13] (applicable in the 10 km range) and to take advantage of the convenience of using the Gaussian model, we have adopted Pasquill's stability classification. We have also converted the relation between $\bar{z}$ and $\bar{x}$ into one between σ_z and $\bar{x}$ with the help of the relation $\sigma_z= a\bar{z}$. The coefficient a is determined by the vertical distribution of the concentration of the pollutant. Regarding the value of a, Pasquill in his earlier work [14] used data from short range atmospheric diffusion experiments to obtain the average value of 1.3. Recently, in his study on mesoscale range vertical diffusion [1], he pointed out that a should be taken as 1.25 (corresponding to a normal distribution of concentration in the vertical direction). At the same time, he pointed out that when the index of distribution γ is 1.5 (2 for normal distribution), a is approximately 1.28, while when the concentration has a distribution lying between the normal distribution and a power law distribution, a varies within the range 1.26-1.42. This shows that, even though the concentration of the pollutant in the PBL does not conform completely to a normal distribution, our choice of a = 1.25 for the calculations will not produce a large error.

Before performing numerical calculations, it is necessary to make reasonable choices for the values of the parameters encountered in the calculations. Our final choice of these values is given in Table 1.

The choice of the values for the thickness h of the PBL as given in the table is based on [15]-[17], height classification for the mixing layer given by Klug (1969) [18], and the experimental results obtained for the measurement of average wind speed and temperature gradient on a 320 m tower [19]. L is taken from the results of [8] and [13]. The parameter l is obtained from the relation $l=\sqrt{\frac{5\times10^{-6}}{K_0}}$. The different stability classes K_0 are chosen from the values given by Draxler [20] in his study on mesoscale range diffusion. These values are also given in Table 1. Later, he [21] also gave the average values of K_0 over each of the seasons as well as the annual average. The chief basis for the values of Q is the formula given by Yordanov [22]:

$$Q(\mu)=5.3+\frac{1}{5.8\times10^{-3}\mu-0.23} \tag{22}$$

We have also referred to [23], [12] and [24] for the selection of Q.

Table 1 Parameters selected for calculation.

稳定度类别 1	h (m)	L (m)	μ	Q	K_0 (m/s)	l (m^{-1})	$\bar{a}_1$ (m)	$\bar{\sigma}_1$ (m)	a
A	3000	−2.5	−1200	5.3	50	10^{-3}	2573	400	0.084
B	1600	−4.5	−333	4.5	30	1.29×10^{-3}	2756	288	0.063
C	1000	−20	−50	3.5	15	1.83×10^{-3}	2830	152	0.060
D	600	>1000	0	1.57	7	2.67×10^{-3}	2864	81	0.045
E	300	75	4	0.55	3	4.08×10^{-3}	3224	32	0.024
F	200	35	6	0.12	1	7.07×10^{-3}	3030	20	0.011

/308

1--stability classification

Table 2 Constants used in expression (23)

稳定度类	A	B	C	D	E	F
a	0.086	0.073	0.064	0.070	0.166	0.233
b	1.12	1.07	1.04	0.876	0.891	0.583
c	1.53	1.23	1.2	1.19	1.12	1.05
d	−29	−56	−57	−59	−58	−96
e	2.95	6.75	5.85	5.4	6.1	8.2

1--stability classification

In Table 1, $\bar{x}_1$ and $\bar{z}_1$ are the initial points for the numerical integration, and have been obtained from calculations using equations given in [8]. The value of α has been obtained by finding by successive approximations that value of α which, after all the other parameters have been selected, gives the computed value of σ_z that best matches the curve given for the range within 3 km in [8]. The results show that α has smaller values for more nearly stable atmospheric conditions. The value for the range of 3-100 km is obtained by inserting the parameters given in equations (11)-(21) and Table 1 into equation (10) and carrying out a numeric integration using Simpson's formula.

After a nonlinear regression analysis is performed on the set of numbers corresponding to σ_z and $\bar{x}$ obtained from numerical calculations, we finally obtain the expression for $\sigma_z(\bar{x}) = G(\bar{x})$ that is applicable in the range of 0.1-100 km:

$$G(\bar{x})=a\bar{x}^{b}/(1+e^{(d+e\ln\bar{x})}) \tag{23}$$

In the above equation, a,b,c,d and e are constants related to stability. Table 2 gives their values for different stability conditions.

IV. EXPRESSION FOR σ_z FOR TERRAINS WITH UNIFORM ROUGHNESS

In order to analyze the expression for σ_z for complex terrains, we adopt the concept of effective roughness length [8], and use the σ_z for a terrain of uniform roughness to represent that for a rough terrain with small nonuniformity. Also, we write the expression for   in the following form.

$$\sigma_z(\bar{x}, z_0) = G(\bar{x}) \cdot F(\bar{x}, z_0). \qquad (24)$$

The $G(\bar{x})$ in equation (24) has been given in the previous section. Except for z_0, the rest of the parameters remain the same. Repeating the above computational process, and dividing the value of σ_z thus obtained by $G(\bar{x})$, we obtain values for $F(\bar{x}, z_0)$ for different stability conditions, different z_0 (0.01-5m) and different values of $\bar{x}$. Nonlinear regression analysis then yields /309

$$F(\bar{x}, z_0) = 1 - a_1 e^{-b_1 \bar{x}} + C_1 \bar{x}^{-d_1} z_0^{e_1} \qquad (25)$$

The constants in equation (25) are listed in Table 3 for different stability conditions.

Table 3 Constarts used in expression (25)

稳定度类 1	A	B	C	D	E	F
a_1	0	0	0.33	1.08	0.65	0.35
b_1	0	0	2.8×10^{-3}	1.6×10^{-2}	3.45×10^{-3}	4.3×10^{-3}
c_1	116	27	30	46	26	16
d_1	1.25	0.8	0.65	0.65	0.5	0.47
e_1	0.900	0.677	0.496	0.552	0.412	0.414

1--stability classification

It can be seen from equation (25) that the effect of z_0 is pronounced only for short ranges. For very large $\bar{x}$, the right hand side of equation (25) approaches 1, and the effect of local terrain features of long range roughness sources can be neglected. This agrees with Hanna's [25] conclusion. However, Hanna only used the power law form of $z_0 P_0$ to express the effect of z_0 in σ_z, where P_0 varies between 0.1 and 0.25. Our result is not just a simple power law expression, and more closely represents the actual situation.

To clearly see the effect of z_0 on σ_z under different stability conditions, we have listed in Table 4 the values of F for z_0 = 0.1,

Table 4 Change of $F(\bar{x}, z_0)$ with stabilities

稳定度类[1] \ $\bar{x}$ (km) \ z_0(m)	0.01				1				5			
	0.1	1	10	100	0.1	1	10	100	0.1	1	10	100
A	1.006	1.00	1.00	1.00	1.36	1.02	1.001	1.00	2.55	1.09	1.005	1.00
B	1.03	1.005	1.001	1.00	1.68	1.11	1.02	1.00	3.02	1.32	1.05	1.01
C	—	1.01	1.01	1.00	2.26	1.32	1.08	1.02	4.09	1.73	1.17	1.04
D	—	1.04	1.01	1.00	3.06	1.52	1.12	1.03	6.36	2.25	1.28	1.06
E	—	1.09	1.03	1.01	3.14	1.80	1.26	1.08	5.90	2.58	1.50	1.16
F	—	1.09	1.04	1.01	2.61	1.62	1.21	1.07	4.35	2.21	1.41	1.14

1--stability classification

1 and 5m, and $\bar{x}$ = 0.1, 1, 10 and 100 km. From this, the following points become apparent: (1) the effect of roughness of terrain increases with increasing stability (A → E). This has been borne out by a large quantity of experimental data [26], and is due to the fact that under unstable conditions, σ_z is mainly controlled by convection and not by mechanical turbulent flow [25]. (2) if $z_0 \leqslant 1$ m, then in the 10-100 km range neglecting the effect of z_0 will only cause an error of about 25%. (3) comparison of the family of curves for σ_z under flat uniform conditions and stability types A-F with the family of curves for uniform roughness shows that the latter are narrower than the former. In [27], a definite conclusion has been drawn to this effect. It has also been pointed out that the P-G curves for type A stability increases rapidly with $\bar{x}$, and are not applicable to complex terrains.

V. EXAMINATION OF RESULTS AND COMPARATIVE ANALYSIS /310

In the above two sections, we have completed the calculations for σ_z. The complete expressions are given by equations (23)-(25) and Tables 2 and 3. In this section, we seek to answer the question of whether these expressions and choice of parameters are appropriate and reflect the actual conditions in the atmosphere.

The result given by Smith for flat uniform conditions is

Table 5 Ratio of σ_z in different models

1. 稳定度类		A		B		C		D		E		F	
2. 距离(km)	z_0(m)	(27)/(23)	(26)/(23)	(27)/(23)	(26)/(23)	(27)/(23)	(26)/(23)	(27)/(23)	(26)/(23)	(27)/(23)	(26)/(23)	(27)/(23)	(26)/(23)
10	0.1	0.94	0.66	1.11	0.66	0.89	0.63	0.7	0.94	0.88	1.32	1.14	1.18
	1	—	0.70	—	0.64	—	0.71	—	1.04	—	1.32	—	1.24
50	0.1	1.43	0.66	1.92	0.76	1.12	0.76	0.76	0.99	0.59	1.45	0.80	1.30
	1	—	0.73	—	0.83	—	0.81	—	1.06	—	1.45	—	1.30
100	0.1	2.0	0.93	2.26	0.90	1.42	0.86	0.63	1.00	0.49	1.49	0.65	1.27
	1	—	1.03	—	1.00	—	0.93	—	1.00	—	1.46	—	1.27

1--stability classification; 2--distance

$$G(\bar{x})=a_1\bar{x}^{b_1}/(1+a_2\bar{x}^{b_2}) \tag{26}$$

Equation (26) has been obtained by performing a numerical solution on the two-dimensional diffusion equation making use of wind speed and vortex diffusion coefficient profiles measured under different stability conditions.

The expression for σ_z used by Wendell in a regional model is

$$G(\bar{x})=a_1\bar{x}^{b_1}/(1+a_2\bar{x}+a_3\bar{x}^2)^c \tag{27}$$

This is a modification and extension of Briggs' [13] interpolation formula. Although equations (23), (26) and (27) are not exactly the same in form, these agree in that there is a difference in diffusivity for short and long ranges, and that the long range diffusivity is smaller. This result is supported by experimental results [30]. and shows that the commonly employed power law form $a_1\bar{x}^{b_1}$ is not applicable to the mesoscale range. For the purpose of comparison, we have listed the ratios obtained by dividing equations (26) and (27) by equation (23) in Table 5.

It can be seen from Table 5 that the three models agree fairly well in the range of 10-100 km. For neutral conditions, the best agreement is obtained between our results and those of Smith, the difference being within 10%. For stable conditions, our results are smaller than Smith's, with ratios lying below 1.5. Our results are, however, larger than those of Wendell. For unstable conditions, results obtained from our model are slightly higher than those of Smith, with ratios lying between 0.56 and 1.03. These are smaller than Wendell's. It is remarkable that these three models which have been derived from different angles of approach are in such good agreement.

/311

We have collected from related literature information on σ_z obtained from mesoscale range measurements made at 10 locations and from estimations from the ground level concentration. There are in all 72 examples taken from diverse sources and for different terrain conditions. Most of these are for stable conditions, with 48 examples for stability types E-F. The least number of examples have been found for unstable conditions with only 12 for stability types A-C. The ranges of measurements for the latter are short (within 20 km in most cases). An analysis of the ratio of calculated to measured values shows that 72% of the ratios are less than 2, 96% of them are less than 3, and only 3% of the data are greater than 3. The total average is 0.93 ± 0.505. Comparison of Smith's model with the experimental data shows that 72% of the ratios are less than 2, 81% of them are less than 3 and 19% of them are greater than 3. The total average in this case is 0.90 ± 0.743. We conclude that there is better agreement between our model and the experimental data, and, therefore, our model is a better description of the actual situation than Smith's model.

VI. CONCLUSION

The following conclusions can be drawn from the numerical analysis given in the above sections:

1. The estimation method of vertical diffusion parameters in the mesoscale range derived from the hypothesis of similarity for local turbulent characteristics has limitations arising from our lack of complete understanding of the variation with height of wind

speed and the turbulent characteristics in the PBL. Some of the relations used in this paper are empirical. Nevertheless, analysis of the ratio of calculated to measured values shows that there is a fairly good agreement between the two sets of values. The average ratio is 0.93 $\pm$ 0.505. For neutral conditions, our results are equivalent to those derived from Smith's model. For stable and unstable conditions, our model is a better description than Smith's.

2. Comparing the variation of σ_z with $\bar{x}$ in the mesoscale range with that in the 10 km range we find that this variation is no longer a simple power law relation, but takes a complex functional form. Even though the three models that we chose for comparison have different forms of expression for this variation, they all have the same tendency, viz. the rate of change of σ_z with $\bar{x}$ becomes smaller with increasing distance. This result is borne out by experimental data.

3. The effect of z_0 increases with increasing stability, and decreases rapidly with increasing distance. For terrains with roughness within $z_0 = 1$ m, if the effect of z_0 is neglected in the range of 10-100 km, only a 25% error will result. However, the importance of z_0 becomes significant for ranges within 10 km.

In summary, although some of the relations used in this paper are empirical in nature, and verification of the results is limited by lack of adequate experimental data, especially for unstable conditions, support for our model is provided by comparison of our results with presently available experimental data and satisfactory agreement with the results obtained from other models. Our method enables one to make use of the increasing amount of available data on the distribution with height of σ_w, λ_m, ε and u to conveniently estimate the vertical diffusion parameter without going through the complicated process of solving the diffusion equation.

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